



Determining Optimal Degree of Soil Compaction for Balancing Mechanical Stability and Plant Growth Capacity

by Wendi Goldsmith¹, Marvin Silva¹, and Craig Fischenich²

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Complexity			Benefit			Cost		
Low	Moderate	High	Low	Moderate	High	Low	Moderate	High

OVERVIEW

Few standards exist for determining ideal design parameters for soil compaction when applying vegetation for stabilization and erosion control of slopes and banks. Geotechnical engineers regularly recommend the highest practical soil compaction based on data correlating soil density with increased mechanical strength. Agronomists, on the other hand, recommend minimal soil compaction because compacted soils are widely understood to impede the growth and development of crops, forests, and native plant communities. Those who design treatments utilizing vegetation for structural performance, generally known as bioengineering, tend to borrow from various fields with a range of outcomes as a result (Figure 1). Therefore, the purpose of this technical note is to present information that can help designers and natural resource managers make decisions regarding soil compaction so as to balance agronomic and mechanical considerations related to the installation and maintenance of bioengineered stabilization treatments.

INFLUENCE OF COMPACTION ON SOIL STABILITY

Soils are compacted to improve the stability of

fills – reducing the likelihood of failures and enhancing safety. Soil fills settle and compress over time. The amount of settlement depends upon the initial compaction rate, among other



Figure 1. Soil is compacted after installing a brushlayer lift. Correct compaction is needed after material installation to close voids and to provide suitable soil density for appropriate plant growth

things. Foundations of heavy buildings, highway roadbeds, and airport runways all require considerable levels of soil compaction for satisfactory performance. Construction of earth-fill dams also involves heavy compaction to provide stable slope faces as well as a uniform and controlled rate of seepage through

¹ The Bioengineering Group, Inc., 18 Commercial St., Salem, MA 01970;

² US Army ERDC EL, 3909 Halls Ferry Rd, Vicksburg, MS 39180

the dam core. The degree of necessary compaction is less clear in earth fills along streambanks because of conflicting project objectives and allowable factors of safety that differ from the examples above.

The effects of soil compaction on the soil strength, compressibility, hydraulic conductivity, and structure have been well-studied (Assouline et al. 1997, Bowles 1992, Lambe and Whitman 1969, Seed and Chan 1959) and a series of standardized testing procedures have become widely adopted by professionals (Hunt 1986). One of the original and most popular tests, the standard compaction test, was developed by R. R. Proctor in the 1930's. The procedure involves compacting three sequential layers of soil in a

4-in-diameter mold with a volume of $1/30 \text{ ft}^3$, using a 5-1/2-lb hammer dropped 25 times from a height of 12 in.

The density that can be achieved using this fixed energy of compaction is dependent upon both the textural composition of the soil and its moisture content at the time of the test (Table 1). The density of the soil is achieved through the close packing of the particles. The lubrication effect of an optimal moisture level allows soil particles to become more easily realigned during the compaction procedure, leading to the highest degrees of compaction. For any given textural composition of soil, there is a maximum dry density that can be achieved at the optimal moisture level using the standard Proctor test (Figure 2).

Table 1. Type of Soil

No.	Description	Sand %	Silt %	Clay %	WL	IP
1	Well-Graded Sand	88	10	2	16	-
2	Well-Graded Sandy Marl	72	15	13	16	-
3	Medium Sandy Marl	73	9	18	22	4
4	Sandy Clay	32	33	35	28	9
5	Silty Clay	5	64	31	36	15
6	Loess Silt	5	85	10	26	2
7	Clay	6	22	72	67	40
8	Poorly Graded Sand	94	6	-	-	-

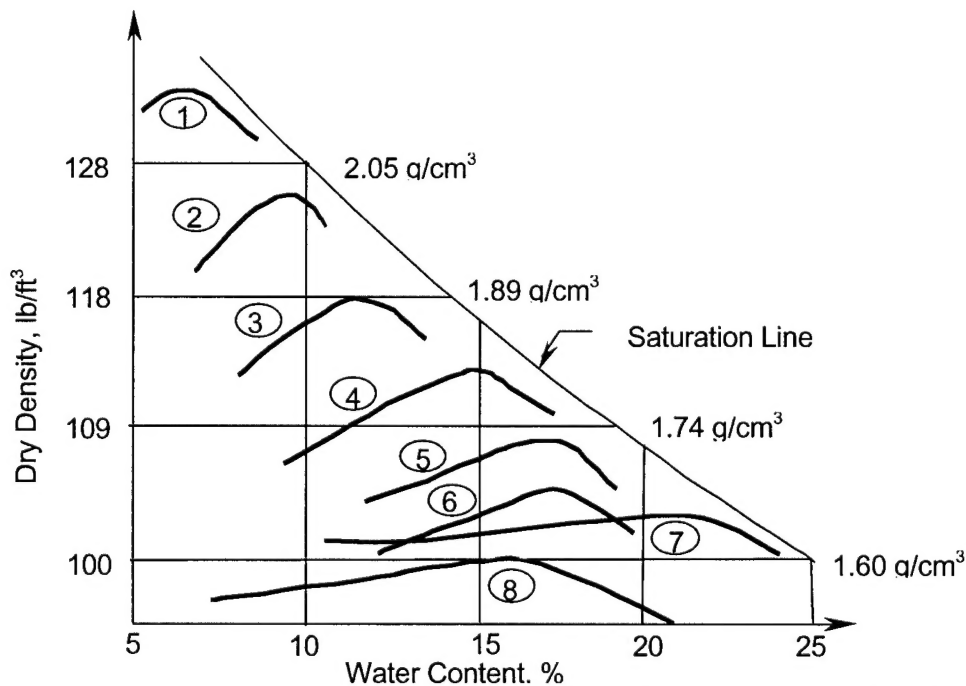


Figure 2. Compaction curves for eight different soils using the standard (AASHTO) Proctor test (modified after Abramson et al. (1995))

In general, compacted granular soils will have higher dry densities in the range of 115 to 135 lb/ft³ (1.84 to 2.16 g/cm³) than those of clayey to silty soils, which are in the range of 85 to 115 lb/ft³ (1.36 to 1.84 g/cm³). The corresponding optimum moisture contents for the granular and silty to clayey soils are generally on the order of 5 to 15 percent and 20 to 35 percent, respectively (Abramson et al. 1995).

Maximum density does not represent a soil condition with no voids remaining, rather one where the tightest possible packing arrangement is achieved given compaction conditions. The point of 100-percent saturation is called the saturation line (Figure 2), which is never reached since some air (pore space) always remains trapped in the soil.

As a general practice, fills that are part of site grading not related to load bearing, are specified to be compacted to 90-92 percent of standard Proctor maximum dry density. Load-bearing soils and other specialized fill applications call for higher compaction levels, including compactations that exceed the values achieved by the standard Proctor test. Once compacted to the selected degree, various parameters of soil strength, including saturated and suction cohesion as well as effective stress envelope, vary with soil type, but all are considerably improved over the uncompacted state (Hunt 1986).

HOW SOIL COMPACTION INFLUENCES PLANT GROWTH

Soil compaction influences plant growth in a variety of ways, both negatively and positively, depending to a large extent on degree and context. These impacts have been studied extensively by agronomists who are concerned with the decline in soil productivity associated with modern agriculture and forestry practices and equipment, which tend to compact soils over time. Observation by the authors of the performance of bioengineering projects throughout the United States provides additional insight into effects of compaction upon plants.

Densities typically sought out by geotechnical engineers for mechanical strength have been shown to reduce or effectively stop the development of roots. When soil compaction levels are high, there appears to be a threshold soil bulk density value beyond which roots are unable to penetrate due to the high mechanical resistance of soils (Figure 3). Review of data for various crops and forest stands growing on a wide range of soil textures reveals limiting bulk densities, which may be used as a predictive tool. Depending on the plant species and the soil conditions, evidence of limits to plant growth range from restriction in root growth, to severe reduction in length of all roots and/or primary root, to no root penetration of compacted soils.



Figure 3. Root penetration of a ponderosa pine (*Pinus ponderosa*) limited by an old compacted roadbed. (Courtesy of Lolo National Forest)

It has been suggested that a growth-limiting bulk density (GLBD) might exist for each given soil texture. Daddow and Warrington (1983) show that it is possible to calculate the average pore radius for a given soil by simulating the packing of soil particles into defined geometric arrangements based on particle size distribution and that GLBD values correlate well with calculated average pore radius. The GLBDs for 80 different soil textures were computed using a regression equation. Daddow and Warrington then plotted on a USDA soil textural triangle in order to locate the growth-limiting isodensity lines shown in Figure 4. These isodensity lines represent equal

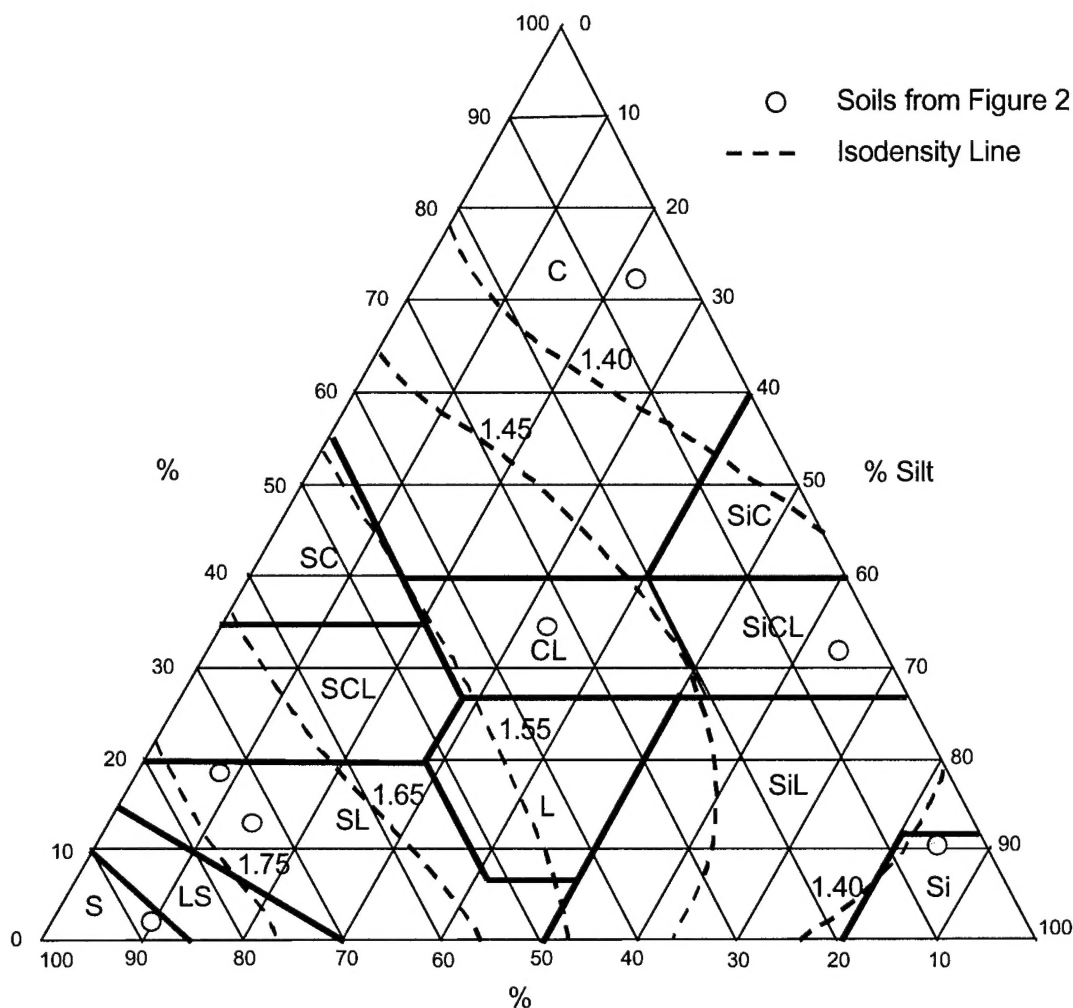


Figure 4. Growth-limiting bulk density textural triangle (Modified from Daddow and Warrington (1983))

GLBD values and are used to estimate the GLBD of a soil.

Some researchers have tried to relate bulk density to factors such as root penetration, soil strength, and compaction (Table 1). These data lead to the conclusion that, in general, non-cohesive soils reach higher maximum dry densities than cohesive soils (Figure 2). Additionally, non-cohesive soils exhibit higher critical dry density than cohesive soils (Figure 4 and Table 1). Sandy soils have large continuous pores, while clays have small pores, which transmit water slowly. Clays, however, contain more pore space than sandy soils.

For growing plants, pore sizes are more important than total pore space. Therefore, plants will have a better environment in sandy soils if porosity is low because of the increase in water retention. The converse is true for clays. High porosity clays have a high macro-movement, which provides high infiltration and more water available for plants.

Coppin and Richards (1990) agree that the critical dry density depends on the soil texture and suggest values of about 87 lb/ft³ (1.4 g/cm³) for clay soils and 106 lb/ft³ (1.7 g/cm³) for sandy soils. These threshold values are within the intervals presented in Table 2.

Table 2. Approximate Bulk Densities That Restrict Root Penetration (from *Handbook of Soil Science* (1999))

Texture	Critical bulk density (g/cm ³) for soil resistance	
	High	Low
Sandy	1.85	1.60
Coarse-loamy	1.80	1.40
Fine-loamy	1.70	1.40
Coarse, Fine-silty	1.60	1.30
Clayey	(Depends on both clay percent and structure)	

It is widely understood that the rooting pattern, including length, areal extent, and internal morphology, are principally controlled by plant genetics, and that soil conditions, as well as other environmental factors, exert a formative influence on the expression of the ideal pattern.

Jaramillo-C et al. (1992) studied the development of moisture-conducting tissues in the new roots of bean plants under varying compaction regimes. Results showed that soil compaction not only limited the length of roots, but the roots failed to properly develop the usual size and shape of metaxylem in high soil bulk densities, resulting in severely reduced transport capacity for water and nutrients. Compacted soils limit capillary radius of roots, which according to Poiseuille's law are able to transport water as a function of the fourth power of the radius. This effect is clearly an issue with new seedlings, and results suggest that problems in early development may persist as plants mature.

Gale, Grigal, and Harding (1991) used a soil productivity index to predict white spruce growth. Their study suggested that soil compaction limits root development and hence nutrient and moisture uptake for younger trees, but that the forest floor becomes the dominant source of nutrients and intercepted rainfall provides moisture as trees mature. Landhaeuser et al. (1996) studied the effects of soil compaction on the depth and lateral spread of marsh reed grass. They concluded that soil compaction is so effective at controlling the growth of this species that superficial soil compaction might be a valuable control technique to prevent the species from

dominating new tree plantations. In summary, compaction to a higher degree than the growth-limiting bulk density for the particular soil can severely limit the short- and long-term growth and development of plants.

The preponderance of information in the literature, supported by the authors' observations, suggests that a compaction between 80 and 85 percent of the standard Proctor maximum dry density provides many of the stabilizing benefits of soil compaction without jeopardizing the viability of vegetation development and growth.

Growth-limiting bulk densities or critical dry bulk densities can readily be compared to standard Proctor maximum dry densities. The critical dry density for each type of soil presented in Figure 2 can be determined by plotting the soils in Figure 4. The degree of compaction suitable for root growth is calculated by dividing the critical dry density by the maximum dry density for each type of soil. Compaction rates thus calculated corresponding to growth-limiting bulk densities vary from 81.9 to 91.0 percent of standard Proctor densities, with an average of 84.1 percent.

INFLUENCE OF VEGETATION ON SOIL STABILITY

Vegetation, both directly and indirectly, influences a variety of processes that lead to increased reinforcement and strength of soils. Under certain circumstances, vegetation can also adversely influence soil stability. Soil compaction affects interactions of water within the soil as well as the growth rate and rooting characteristics of vegetation. These, along with the increased tensile strength from the root systems and the armoring effect of plant components against erosion, are the primary influences of vegetation on soil stability. Growing plants constantly remove water from the soil, increasing the matric suction and, thus, compacting the soil. This process can be visualized using the constitutive surface from soil mechanics (Figure 4). In Figure 4 the vertical axis represents the void ratio (e), the right axis is the matric suction ($u_a - u_w$), and the left axis is the net normal stress ($\sigma_n - u_a$). A soil compacted to 85 percent Proctor will have an

initial void ratio e_0 . The plant roots will be extracting water from the soil, increasing the matric suction up to the wilting point. During this process the soil is said to be consolidating, reducing its void ratio from e_0 to e_f . This means that plants will be creating a suitable soil density environment. When plants remove water from the soil through evapotranspiration, the associated matric suction increases the soil shear strength.

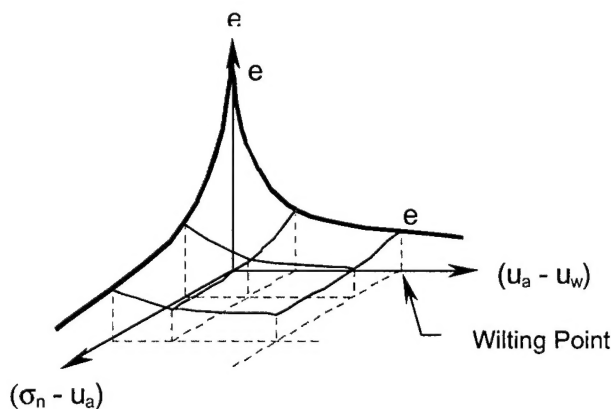


Figure 4. Constitutive surface of soils

Shear strength is also increased through root cohesion. The density of roots within the soil matrix, as well as their orientation, tensile strength, and length, affect the ability of soils to resist shear stress. As deformation begins to occur within a mass of soil, any roots that extend across the zone or plane of movement are placed under tension. Assuming that roots are well-anchored and do not pull out, the shear force is resisted by the tensile properties of the roots (Greenway 1987). In practice, the presence of roots often serves to significantly increase the strength of soils, in some cases by more than an order of magnitude.

The shear strength of unsaturated soils can be assessed within conventional slope analyses by using the total cohesion method. The total cohesion (c_T) includes three components: effective cohesion (c'), suction cohesion (c_ψ) and root cohesion (c_R) (Silva 1999). The shear strength (τ) of the unsaturated soil may be written as

$$\tau = c' + c_\psi + c_R + (\sigma - u_a)\tan\phi$$

where $(\sigma - u_a)$ is the net normal stress and ϕ is the angle shearing resistance. This equation suggests that the soil shear strength is enhanced by evapotranspiration and the root biomass. The suction cohesion varies with changes in the soil moisture, making it difficult to predict. However, soils become stronger and the effective cohesion tends to increase due to the hysteresis phenomenon caused by the wetting and drying cycles. Specific plant communities can sometimes be designed and managed for a net export of water from a site.

Vegetation on slopes generally helps to promote infiltration of water into soils. This process commences when raindrops are intercepted by plants, funneling rainfall gently down stems, or allowing it to drip slowly off leaves rather than directly striking the soil surface, which often leads to crust formation due to compaction and reworking of exposed soil surfaces. Accumulated organic litter, combined with the roughness derived from living plant stems and foliage, helps to detain water, which might otherwise leave the area as runoff, thus increasing infiltration. Organic matter that becomes incorporated into the soils also improves the capillarity of soils and enhances water retention.

Water is a limiting factor on many sites with erosion problems, and processes that help to increase the availability of water generally improve the survival and recruitment of vegetation. Root channels and biopores increase the conductivity of soils to allow efficient infiltration and drainage. While increased moisture levels almost always lead to an improvement in surface erosion problems, excess soil moisture is often the cause of deeper-seated soil instability. Evaluation of this problem is complex, but under many circumstances the presence of vegetation can improve conditions by enhancing internal drainage of soils through root channels and biopores. At higher soil compaction rates, the increase of infiltration and conductivity rates of soil by vegetation becomes more pronounced, until the point when plants cease to develop effectively.

A common best management practice, especially for slopes, is to establish and

maintain vegetative cover, typically of turf-forming grasses, in order to prevent surface erosion. Vegetation shields soils from rain splash and helps to prevent sheet and rill erosion. Vegetation-lined swales and vegetated riverbank and lakeshore treatments demonstrate similar benefits in more highly erosive settings. Roots that develop into dense mats perform as a separating filter layer to prevent fine particles from being removed by forces of traction and suction. Leaves and stems dissipate wave energy and slow flow in the zone nearest the soil surface, thus providing a localized reduction in forces. Vegetation can provide protection against surface erosion even in settings with highly compacted lower soil horizons, provided rooting can occur in the upper horizon.

Depending on the geomorphic context, roots can penetrate through discontinuities in soil and bedrock strata in order to provide special slope-stabilizing functions (Greenway 1987). An individual deeply rooted tree can reinforce a column of soils and anchor weaker mantle soils to more stable bedrock or compacted soils below. The region of soils positioned upslope from the tree can also be stabilized through buttressing. When two or more points on a slope are similarly anchored, an additional zone upslope and between the two anchored columns of soil is stabilized by virtue of arching, which develops within the mantle soils. These effects are only noteworthy if roots are capable of penetrating from a less stable soil mantle to a more stable layer below. Compaction that limits root penetration may prevent the attainment of these benefits.

The mass and leverage of vegetation, especially large trees, can also promote soil instability. Surcharge loading associated with heavy trees can increase the likelihood of deep-seated failures in some cases. Trees that are wind-thrown or uprooted by flowing water can generate local turbulence that increases erosion and scour.

Generally, data show that vegetated soil slopes are more stable than unvegetated soil slopes in terms of geomorphic processes, and without consistent intervention most slopes naturally vegetate over time. Much of this stability is

derived from soil structure, which is promoted by biological activity, rather than the attributes readily analyzed through conventional testing (Burmister 1965). Soil systems that are well-vegetated and maintain fundamental physical properties including normal ranges of bulk density can perform biogeochemical functions which poorly managed soils cannot (Parr et al. 1992). Although these functions may not be a recognized priority in all current design considerations, they are becoming more widely understood. In river corridor and lakeshore settings, the role of healthy soil and vegetation buffers is well-appreciated and soil stability and erosion control functions have been successfully combined with water quality functions through bioengineering design.

PRACTICAL CONSIDERATIONS OF SOIL COMPACTION SPECIFICATIONS IN BIOENGINEERING

In general, a compaction between 80 and 85 percent of the standard Proctor maximum dry density optimizes slope stability with vegetation development and growth. If superficial erosion control is the only need; for example, when the angle of repose for unconsolidated soils can easily be met, then soil compaction may be a needless expense that is readily omitted from the design. In many situations, it may be appropriate to compact base soils over bedrock to a high degree for mass stability, and plant upper soil mantle layers for superficial erosion control. However, compacted soils should not inhibit lateral movement of water. In all cases, soils that fail to be compacted to at least typical field bulk densities are vulnerable to considerable settlement and slumping as well as surface erosion, all of which pose short- and long-term problems for plant development.

There is some delay between the introduction of vegetation and the start of its active role. If the slope is in a critical condition at this stage, a high degree of compaction may protect the slope against failure, but root growth will be restricted. In this situation, the geotechnical requirements should be addressed using some initial safeguard against failure such as biodegradable and synthetic geotextiles, live or

dead wooden stakes, metal pins or spikes, soil nails, or a retaining structure. This will provide a temporary engineering function until vegetation takes root and grows. Stability analyses should be conducted on the short- and long-term slope condition, with and without the vegetation effects.

A soil compacted to 85 percent Proctor will not provide a significant engineering function to the stability of slopes, but it will provide a suitable environment for roots to grow. However, the initial loose condition of the soil is only temporary.

Achieving desired soil compaction rates always requires careful attention in the field, as exact soil textural characteristics and daily moisture levels are highly variable. It is essential to test soils, using sufficient samples to adequately reflect the variability of the site in order to develop meaningful criteria for soil compaction. Tests of both particle size distribution and standard Proctor densities are helpful additions to standard agronomic tests. The adequacy of compaction procedures should be evaluated on a daily basis during construction (Figure 5). Otherwise, even the best-conceived specifications are unlikely to be consistently followed (Burmister 1965). Both the testing and inspection requirements should be identified in the specifications. Unwanted soil compaction, for instance on haul roads and staging areas, should also be addressed in the design and specifications.

CONCLUSIONS

In conclusion, vegetation measures and soil compaction standards are compatible provided that suitable densities are maintained to allow for root penetration. Design approaches must suitably account for site-specific geomorphic conditions as well as short- and long-term goals. When thoughtfully integrated, vegetation and soil compaction can serve as complementary design elements to provide highly effective treatments that function synergistically.



Figure 5. Soil density can easily be checked in the field using portable equipment such as a gamma probe

The wide range of ancillary attributes (water and air quality benefits, improved aesthetics, habitat functions, self-maintenance, and self-repair), and cost-effectiveness make bioengineering an attractive choice over standard geotechnical engineering. The knowledgeable specification and proper execution of soil compaction can greatly enhance the outcome of a range of bioengineering projects.

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POINTS OF CONTACT

For additional information, contact Dr. J. Craig Fischenich, (601-634-3449, fischec@wes.army.mil), or the manager of the Ecosystem Management and Restoration Research Program, Dr. Russell F. Theriot (601-634-2733, therior@wes.army.mil). This technical note should be cited as:

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